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AUTHORITY

SAMSO USAF ltr, 28 Feb 1972

REPORT NO. AE 62-0171

DATE 21 February 1962

NO. OF PAGES 14

CONVAIR | ASTRONAUTICS

CONVAIR DIVISION OF GENERAL DYNAMICS CORPORATION

ELECTROSTATIC CHARGING IN F SERIES ATLAS FUEL SYSTEM

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REVISIONS

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I. SUMMARY

A. PURPOSE AND SCOPE

This study was conducted to determine the probability of the existence of an electrostatic charging hazard in the F Series Atlas Fuel Transfer System. A further intention was to investigate test procedures to evaluate the degree of the problem and possible solutions if a hazard seemed probable.

B. CONCLUSIONS

All available information indicates that electrostatic charging presents a definite hazard in the Silo Fuel System. Fatal explosions and/or fires are possible. The most dangerous operation is catchment tank loading and unloading. Here highly charged fuel is expected to enter the atmosphere-vented catchment tank and the open tank trucks respectively.

The missile fuel tank seems safe due to nitrogen inertion of the ullage atmosphere. Nevertheless, further investigation is necessary.

C. RECOMMENDATIONS

It is recommended that an antistatic additive be mixed with RP-1. The hazard can definitely be eliminated in the entire fuel transfer system by use of such an additive. This solution is extremely easy and inexpensive although the additive's side effects require evaluation. Until these side effects are investigated, it is suggested that a nitrogen purge system be applied to the catchment tank and tank trucks as an interim solution. It should be noted that the nitrogen purge does not eliminate the possible hazard in the missile tank where an ullage gas analysis is needed to determine ullage atmosphere flammability.

Alternatively, the degree of the electrostatic charging hazard can be investigated by means of tests at OSTF-2 (Vandenburg AFB). The extent of the test program must be a compromise between the quantity of data necessary for the degree of safety desired and the economics of the situation in terms of time and money.

The relative merits of these approaches should be investigated. In the mean time, it is recommended that personnel be kept at a safe distance during fuel transfer operations considered dangerous.

II. INTRODUCTION

A. BACKGROUND

The possibility that electrostatic charging of RP-1 rocket fuel may constitute a hazard was first considered in early December 1961, by the Propellant Loading System Design Group, because of several features unique to the F Series Atlas. The point was raised, quite incidentally, by Dr. Grey, a former consultant to Convair Scientific Research Laboratory, and now a professor at Alfred University, Alfred, N.Y., in a discussion concerning the Fuel Purification Unit. He pointed out that the extremely low total water content of the processed fuel could reduce fuel conductivity to a value conducive to electrostatic charging. A study was therefore initiated to determine if a problem could exist, to investigate techniques to evaluate its extent, and to determine possible solutions to the hazard.

A survey of available literature and phone conversations with experts of Esso, Shell, and Atlantic Research Corporation indicated that a problem may very well exist. It was then decided to confer with these experts in detail. Dr. J.H. Jaffer, Jr., Mr. A.L. Ludwig, and Dr. Micheal Markels, Jr., of Esso, Shell and Atlantic Research respectively, as well as other people from these firms, graciously gave much of their time to this study in personal discussions in late January.

B. HISTORY OF PROBLEM

Electrostatic charging has long been a problem in refineries. Many fires and explosions have been attributed to electrostatic sparking in storage tanks, tankers, and tank trucks. The Standard Oil Company (New Jersey) and Affiliates list eighteen fires and/or explosions (1) caused by static ignition. Other oil companies, too, have experienced static explosions all over the world. More recently, military aircraft have been involved. The CF-100 RCAF fighter episode is particularily well documented. Seven incidents, two of which resulted in explosions, occured in the winter of 1957. An on-the-spot, full-scale study was made by Dr. D.T. Rogers and J.C. Munday of Esso Research and Engineering Company, yielding important data (2).

No incidents have been reported with commercial aircraft although increasing fueling rates and purer fuels have created enough concern to result in several studies. Esso and Shell have performed extensive laboratory and full scale experiments in the last several years. The Coordinating Research Council, in cooperation with many oil companies, airlines, and Convair Division of General Dynamics Corporation, conducted an extensive program last year. One objective of the CRC study was to evaluate the use of a scale model for further electrostatic studies. Agreement between the full scale equipment and the model was fairly good. Atlantic Research Corporation, Alexandria, Va., also participated in this study and is now in possesion of the scale model.

The results of this work indicate that a definite hazard exists when aviation type kerosenes are pumped into aircraft tanks. Esso and Shell have developed an antistatic additive which, in concentrations of 1 ppm, increases fuel conductivity to the point where no charge can accumulate (9,3). The additive's side effects, however, are as yet not fully evaluated.

III. ELECTROSTATICS AND PETROLEUM PRODUCTS

A. GENERAL

Electrostatic charging is, of course, not confined to liquid hydrocarbons but only this aspect will be considered. Electrostatic charging can occur whenever there is motion of a fuel relative to a second substance which may be a solid, liquid,or gas. A point in case is the flow of fuel along pipes and through filters. Less obvious is the relative motion of fuel spray, vapor, or mist and air through which it may be forced. The charge generation mechanism is not entirely understood. The general opinion is that charge separation occurs at the interface of relative motion, that is, ions of one sign (present as impurities in the fuel) are more readily adsorbed at an interface surface than ions of the other sign. In the case of fuel flowing in a pipe, for example, negative ions are thought to be adsorbed by the pipe surface. This leaves the fuel with a net positive charge as it enters the tank. A negative charge is then induced on the inside surfaces of the tank and so an electrostatic field, much as the electric field between oppositely charged capacitor plates,is established. Field strengths of several hundred thousand volts per meter are not unusual, and values in the millions are thought to be possible.

It should be noted that grounding a tank does not remove the induced charge on the inside surface. To clarify, take the example of positively charged fuel in an ungrounded tank. By induction, electrons (negative charges) tend to migrate to the inside surfaces of the tank. This in turn leaves a net positive charge on the outside surface of the tank. Grounding the tank neutralizes this "outside" charge by allowing electrons from ground to flow to the outside surface. The "inside" charge, held by induction, remains.

If the electric field in the ullage space of a tank exceeds the potential breakdown value of the ullage atmosphere, a discharge occurs. The resulting spark may be of a high enough energy to ignite the mixture of air and hydrocarbon vapor in the ullage. Less probable, but nevertheless possible, is structural damage by intensive sparking even without ignition. These are the hazards of electrostatic charging.

B. CONDUCTIVITY

In any electrostatic study, the fuel conductivity is of primary importance. Electrical conductivity is largely a function of ion concentration. If very few ions are present, obviously not much charge separation and accumulation can occur and electrostatic charging is not a hazard. This is the situation in a chemically pure fuel and is not expected to be encountered in the field. If ion concentration is high, electrostatic charging is again no problem since, although much charge separation occurs, charges generated combine almost immediately through the highly conductive fuel and no accumulation is possible. It becomes apparent, then, that electrostatic charging is only a problem when the fuel falls into a certain conductivity range. This range is approximately 0.1 to 10 picomhos per meter. Unfortunately, aviation kerosenes, which include RP-1, have a conductivity almost "ideal" for charge generation. In a world wide survey, Esso reports that 10% of all aviation kerosenes tested have a conductivity of less than 1 picomho per meter and 90% have a conductivity of less than 10 picomhos per meter (3). In other words, 85% of the samples had a conductivity value between 0.1 and 10 picomhos per meter.

Electrical conductivity of petroleum fractions is not ohmic, that is current is not proportional to field strength, and, in addition, depends on time. This causes some problems since measurement results obtained depend on the applied voltage and at the time readings are taken. Both Esso and Shell (4,5) have conductivity measurement procedures available.

Esso's method consists of measuring current with a known applied voltage and using Ohm's Law to obtain the resistance. Current is plotted as a function of time and the equilibrium value of current is used to compute the resistance. The equilibrium value of the current can be estimated by extrapolating the curve after a few measurements or current can be read to the bitter end which may take 30 minutes.

With Shell's method, the conductivity is calculated from the time required to reduce a potential difference across a capacitor to a certain fraction of its original value. The petroleum product under test is used as the dielectric in the capacitor.

Both methods require skill and carefully calibrated equipment.

Conductivity is affected by filtering equipment of all types, by the contamination in a fuel transfer system, and by electric fields. In addition the conductivity of RP-1 will vary with the supplier and even with different batches of the same refinery. The variation with field strength gives rise to "effective" conductivity. This is the conductivity which actually exists in the charged fuel and which determines the rate of charge dissipation to ground or "relaxation". It can be several times higher or lower than conductivity measured at "rest" although it is usually lower (6).

It can be seen, then, that conductivity measurements are by no means simple. To have any value, measurements must be made with RP-1 from each supplier and before and after filtering equipment.

C. FLOW RATE

In general, the faster a fuel travels over a surface the more charge is separated and the hazard is increased. The exact relationship is not known but charge generation seems to vary with slightly less than the second power of flow velocity. No range, outside of which electrostatic hazards do not exist, can be established here as is the case with conductivity. Flow rates in the F Series Atlas fuel transfer system vary from 5 to 27 ft. per second in stainless steel pipes and rubber flex hoses. Sparking was observed in two studies at lower flow rates (6, 14).

D. GEOMETRY

The geometry of a particular fuel transfer system greatly effects charge generation and sparking. The surface area, for example, encountered by the fuel is important since electrostatic charging is a surface phenomenon. Filters and filter-separator type devices present a large surface area to the fuel and so the charge generated in them is much higher than the charging in pipes. In fact, piping after the final filter usually serves to relax the charge in the fuel as it travels to the tank.

A particularily troublesome situation exists when a filter is placed just upstream of a tank. Almost all of the charge generated in the filter will then be carried to the tank since no relaxation is possible.

As the charged fuel rises in a tank an electrostatic field is established between the fuel surface and the tank ceiling, walls, and other surfaces, such as instrumentation devices. It is well known that local field strengths become relatively high when irregular and pointed surfaces exist although they would be low in a "smooth" tank.

Thus, when the electric field is distorted by irregular geometry, sparking is more likely to occur. In air, for example, 1000 kv/ft. is quoted as the breakdown potential of air between parallel plates. If pointed electrodes are used, the breakdown potential is much less. It is estimated that, under ideal conditions, incendiary sparks could be produced by a liquid surface potential of the order of one kilovolt (2).

IV. ATLAS SYSTEM CONSIDERATIONS

A. THE FUEL TRANSFER SYSTEM

The Atlas fuel system consists of the missile tank, the catchment tank, the fuel purification unit, the fuel loading prefab, and the interconnecting piping. The system will handle fuel much of which is expected to have an ideal conductivity for electrostatic charging. The flow rates involved are higher than the C&C study flow rates where sparking occured. The geometry, too, seems conducive to charge generation due to several filtering devices. A stainless steel mesh filter is located in the fuel loading prefab and a filter separator may be mounted on the Air Force tank trucks. The fuel purification unit is one huge filter consisting of a filter-separator, three desiccant beds, and a backup filter. When the previously mentioned experts were acquainted with the system, their strongly expressed opinion was that a hazard exists in some phases of fuel transfer.

The fuel system can be divided into four operational procedures for electrostatic studies:

1. Missile Loading

Fuel flows from the catchment tank or tank trucks to the missile. (It is the intent to flow through the Fuel Purification Unit whenever fuel is delivered into the missile tank).

2. Catchment Tank Loading

Fuel flows from the missile or tank trucks to the catchment tank.

3. Tank Truck Loading, Fuel Purification Unit Validation

Fuel flows from the missile or catchment tank to the tank trucks. (The Fuel Purification Unit will be used to pump fuel from the catchment to the trucks during FPU validation).

4. System Validation

Fuel flows from the tank trucks thru the Fuel Purification Unit, thru the silo fuel plumbing, thru the Fuel Loading Prefab, back to the tank trucks.

The experts agreed that the worst case, as far as charge generation is concerned, is tank truck loading (using the fuel purification unit) followed by catchment tank loading from tank trucks. In each case fuel is pumped through a filter shortly before it enters a tank with a flammable atmosphere. The other operations were judged fairly safe since either no filter is in the circuit or tank ullage atmosphere is inserted.

B. MISSILE FUEL TANK

The missile fuel tank, it was felt, is probably safe due to nitrogen pressurization and similarity to earlier Atlas arrangements where no problem has been identified. The missile tank ullage atmosphere, pressurised to approximately 14 psig with nitrogen, will probably not support combustion under any conditions. It was pointed out, however, that it is just possible that the evolution of dissolved oxygen in the fuel plus the injection of air, trapped in the fuel fill and drain line, during a leveling operation, may create a flammable ullage atmosphere. It was felt, therefore, that an ullage gas analysis, under the worst possible expected conditions, should be made.

C. CATCHMENT TANK

Catchment tank loading from tank trucks through the truck mounted filter-separator will result in charged fuel entering the atmosphere-vented tank. Whether or not the charge is high enough to cause sparking is impossible to determine without tests. The experts opinion was that a hazard probably exists.

It should be noted that, in spite of GD/A objections, the silo facility fuel catchment tank was designed without an inert atmosphere. No other Atlas tank is vented directly to the atmosphere.

D. TANK TRUCKS

The ullage atmosphere in the truck tanks will certainly be flammable and explosions could result. Unloading the catchment tank thru the Fuel Purification Unit into tank trucks, as previously noted, was considered the most dangerous operation. This is based on the assumption that the Fuel Purification Unit is an efficient electrostatic generator. Highly charged fuel, it was felt, will enter the tank trucks since not much relaxation can occur in the 12 ft. section of hose provided at the outlet of the FPU.

V. ELECTROSTATIC MEASUREMENTS

A. GENERAL

Testing in connection with electrostatic charging studies is difficult. Equipment not usually available is required for field strength and charge density measurements. Experience with measurement techniques is highly desireable both for the actual testing and for the analysis of the test data.

B. DATA REQUIRED

Five types of measurements are used to evaluate the extent of an electrostatic problem. Although all five may not be necessary here, they are given below:

1. Fuel Conductivity
2. Field Strength
3. Charging Current
4. Charge Density
5. Charging Tendency

Conductivity measurements were described in Section III A. This measurement is required.

Field strength measurements are most difficult. Instrumentation is not commercially available although approximately six field meters exist in the United States. These meters were built by Esso and Shell and their loan is possible. The instrument picks up and amplifies a small alternating voltage which is induced in a rotor alternately exposed to and shielded from the electrostatic field. The device must be carefully calibrated and properly installed in a region where high field strengths are expected. This usually presents difficulties due to inaccessibility.

Charging current is measured by allowing the charge induced by the fuel in an electrically insulated portion of the system (usually a filter) to flow to ground through a micro-micro ammeter. The insulation used is Teflon. An entire tank truck, for example, can be isolated by driving it onto cleaned Teflon plates and by installing Teflon gaskets in inlet and outlet piping. The truck is then connected to ground thru the current meter and the current measured is a good indication of the fuel's charge density. Mr. A.L. Ludwig of Shell felt that conductivity and charging current measurements may suffice to define the Atlas electrostatic problem.

Charge density measurements employ instrumentation similar to the field meter discussed above (6). The device is usually installed in an elbow with the probe centrally located in the fuel flow path. The charge density, in microcoulombs per cubic meter of the fuel can then be deduced from the amplitude of the induced alternating voltage.

Charging tendency of a fuel is measured by comparing the number of sparks produced by different fuels under the same laboratory scale transfer condition (7). This measurement is not recommended since too many variables affect the data. Temperature and storage time, for example, effect the sparking rate in a seemingly unpredictable manner.

In order for sparking to present a hazard, a flammable atmosphere must exist near the spark. The ratios of hydrocarbon vapor and air, as a function of temperature, which support combustion are well known. Where doubt exists as to the flammability of an ullage atmosphere, it is desireable to perform a gas analysis since electrostatic measurements are expensive and useless if a gas analysis indicates combustion is impossible.

VI. DISCUSSION

A. GENERAL

If the extent of electrostatic charging in the fuel system is to be evaluated, some sort of test program must be conducted.

The testing can be performed by Astronautics alone, by Astronautics with help from Esso, Shell and Atlantic Research on a consultant basis, or the test program may be subcontracted to an experienced firm in part or entirely.

The Atlantic Research Corporation, which took part in the CRC studies and presumably has good testing experience, is seeking contracts of this nature. It should be noted that the firm does not have field meters but they are apparently capable of building them to Shell drawings. The complete testing program was estimated to cost $65,000. It is also possible to obtain consultants from the firm if this should be desired.

Esso and Shell normally are not contracted for this kind of small task, but consultation is available. An attempt to subcontract to Esso or Shell is, of course, possible.

Any test program should involve the actual equipment presumably at OSTF-2 where schedule problems will arise. Testing of this type is expensive and it is recommended that whichever way it is carried out, it be complete the first time.

B. TEST PROCEDURES

The experts consulted disagreed somewhat with what an adequate test setup might be. Obviously it would be desireable to run all tests under many different conditions and to draw conclusions from a wealth of data. Economics and time, however, dictate a different approach.

Shell indicated that conductivity and charging current measurements may be enough to evaluate the problem. This would mean measuring tank truck and FPU charging current and fuel conductivity before and after filtration. Investigation of the missile tank ullage atmosphere was also recommended.

Esso felt that, in addition to conductivity and charging current, field strengths in the catchment tank and the tank trucks should also be measured.

Atlantic Research recommended that conductivity, field strength (in catchment tank and tank trucks) and charge density measurements be made. It was also recommended to install a photoelectric cell in the vicinity of expected sparking.

C. SOLUTIONS TO PROBLEM

Several solutions to electrostatic charging problems are known. They are listed below. It should be noted that applying a solution may be less expensive than conducting an exhaustive test program. This is especially true when the existance of a problem is strongly suspected. A program verifying a

hazard still leaves the task of eliminating this hazard.

1. Reduction of flow rates

A lower fuel velocity reduces charge separation but does not give absolute protection since this is a matter of degree. Testing must accompany such a fix.

2. Removal of final filter

Filters are potent charge generators. The final filter (the first filter upstream of the tank being filled) is especially dangerous since the charge generated in it does not usually have much relaxation time, i.e. the final filter is usually close to the tank. Removal of this filter again is not a positive fix and testing is necessary. In addition, the removal of a filter may be undesireable in a given system.

3. Provision for relaxation volume

Charge accumulated in fuel dissipates (relaxes) with time. Thus, if additional piping or a tank is introduced between the final filter and tank to provide sufficient relaxation time, much of the charge will have disappeared. However, the relaxation volume necessary can become unacceptabley large if constructed to provide positive protection for low conductivity fuels.

The relaxation volume necessary to achieve the desired degree of charge dissipation can be calculated. Charge dissipates or relaxes in accordance with the equation

$$Q_T = Q_o e^{\frac{-tk}{\epsilon \epsilon_o}}$$

where Q_T = charge density after time t

Q_o = initial charge density

t = elapsed time in seconds

k = fuel conductivity in mho/cm

ϵ = fuel dielectric constant

ϵ_o = 8.85×10^{-14} farad/cm

Example: Assume $k = 1 \times 10^{-14}$ mho/cm $= 1 \times 10^{-12}$ mho/m

and $\epsilon = 2.3$ (approximately)

If it is desired to reduce the initial charge density by 60% ($\frac{Q_T}{Q_o} = 0.4$) a relaxation time of approximately 20 seconds is needed. At a flow rate of 300 gallons per minute, a 20 second relaxation volume equals 100 gallons. It follows then that a 100 gallon tank is needed to reduce the initial charge by 60% of its value under the above assumed conditions.

4. Inerting of ullage atmosphere

If the ullage atmosphere is inerted, no combustion can take place. Discharges are not eliminated but spark energies are not high enough to cause structural damage when such sparking occurs from the fuel to a conductor.

5. Adjustment of fuel volatility

Here the fuel's properties are controlled so that flammable atmospheres are not created under expected conditions. For example, if the vapor pressure were increased so that a non flammable, over-rich mixture exists in the ullage, no fire or explosion could be caused by sparks. It is difficult, however, to alter one physical property of a fuel without affecting others and therefore a "new" fuel would have to be evaluated.

6. Radioactive source in ullage space

A radioactive source ionizes the ullage atmosphere so that it can act as a conductor. Charges in the fuel can then flow through the ullage to the tank and ground. Further study is necessary if this solution is to be considered.

7. Grounded, floating conducting grid on fuel surface

Here again a conductive path is provided for the charge distributed in the fuel. Difficulties include construction and inaccessibility.

8. Antistatic additives

These additives increase fuel conductivity to the point where charge accumulation is not possible. Side effects of the additives have not been evaluated for rocket engine systems.

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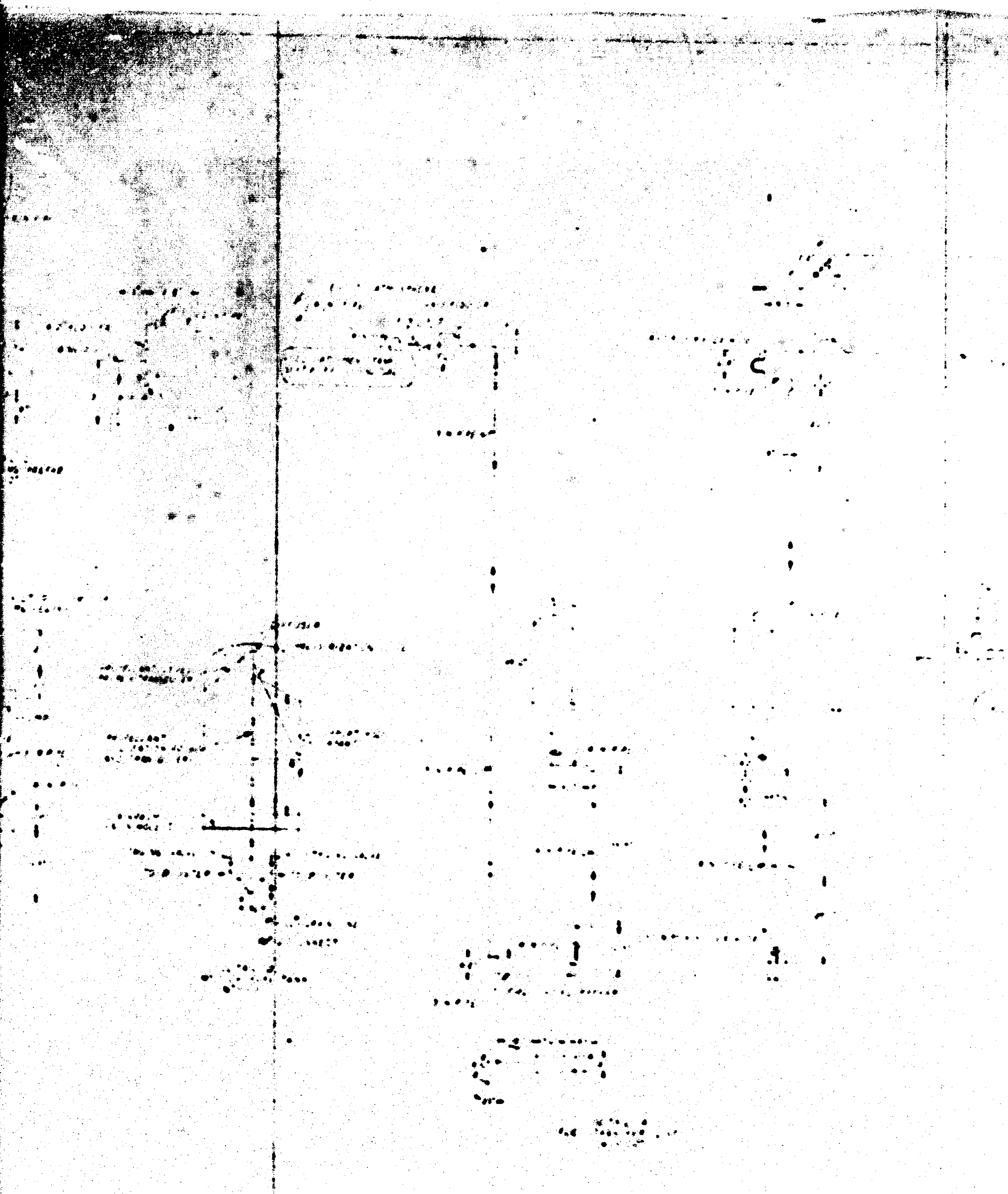

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